V. Heterojunction Bipolar Transistors

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AlGaAs/GaAs heterojunction bipolar transistors (HBTs) are used for digital and analog microwave applications with frequencies as high as Ku band. HBTs can provide faster switching speeds than silicon bipolar transistors mainly because of reduced base resistance and collector-to-substrate capacitance. HBT processing requires less demanding lithography than GaAs FETs, therefore, HBTs can cost less to fabricate and can provide improved lithographic yield. This technology can also provide higher breakdown voltages and easier broad-band impedance matching than GaAs FETs.

In comparison with Si bipolar junction transistors (BJTs), HBTs show better performance in terms of emitter injection efficiency, base resistance, base-emitter capacitance, and cutoff frequency. They also offer good linearity, low phase noise and high power-added efficiency. Table 3-3 shows a comparison of typical device characteristics between AlGaAs/GaAs HBTs and Si BJTs. HBTs are used in both commercial and high-reliability applications, such as power amplifiers in mobile telephones and laser drivers.

Table 3-3. Comparison of AlGaAs/GaAs HBT and Si bipolar transistors.

Parameter	AlGaAs/GaAs HBT	Si BJT
Forward transit time, τ_F	4 ps	12 ps
Early voltage, V_a	800 V	25 V
Collector-substrate capacitance, C_{cs}	~0	~15 fF
Base resistance, R_b	70 W	200 W

For NPN BJTs, a useful figure of merit that is important in determining the current gain is the ratio,

$$\frac{\textit{electron current injected from the emitter into the base}}{\textit{hole current injected from the base into the emitter}}$$

This ratio is called the injection efficiency, and it is usually optimized in BJTs by highly doping the emitter and lightly doping the base. High injection efficiency is obtained in an HBT by using a material with a larger energy band gap for the emitter than that used for the base material. The large energy band-gap emitter blocks injection of holes from the base. Therefore, the doping concentration in the base and emitter can be adjusted over a wide range with little effect on injection efficiency. In the normal operation of a bipolar transistor, the collector-base junction is reverse biased or at least not forward biased enough to cause appreciable injection current. The collector and base material are the same in most HBTs, although some use wide band-gap collector materials to improve the collector base breakdown voltage.

It follows that AlGaAs/GaAs HBTs benefit from the following advantages:

(1) Lower forward transit time along with a much lower base resistance (due to the much higher base doping concentration), giving increased cutoff frequency f_t.

(2) Better intrinsic device linearity due to a higher beta (gain) early-voltage product.

(3) Very low collector-substrate capacitance C_{cs} in AlGaAs/GaAs HBTs due to the use of semi-insulating GaAs substrate (resistivity $\approx 10^7$ Ohm-cm).

(4) High efficiency due to the ability to turn off devices completely with a small base voltage change and the extremely small turn-on voltage variation between devices.

(5) Good wide-band impedance matching due to the resistive nature of the input and output impedances.

(6) Low cost and potential for high throughput. With the typical minimum feature size of 1 μm, there is no need for e-beam lithography.

A. Device Structure

The cross section of an example HBT is shown schematically in Figure 3-17. The material on which an HBT is fabricated is grown on a semi-insulating GaAs substrate. These epitaxial layers could be grown by molecular beam epitaxy (MBE) or the metal–organic chemical vapor deposition (MOCVD) method. A heavily doped n^+ GaAs layer with a concentration on the order of 4×10^{18} cm^{-3} is grown first for the collector contact, followed by a lightly doped n GaAs layer for the collector. The collector doping concentration is on the order of 3×10^{16} cm^{-3}. A heavily doped p^+ GaAs layer with a concentration greater than 5×10^{18} cm^{-3} is used for the base. In general, beryllium (Be) or carbon (C) is used for the base dopant. Again, a wide-band-gap AlGaAs layer is grown for the emitter. Finally, a heavily doped n^+ GaAs layer is grown to facilitate the fabrication of low-resistance ohmic contacts. An n^+ InGaAs-alloy contact layer can be also grown to provide stable, low-resistance emitter contacts. Some HBTs utilize compositional grading on both sides of the emitter-base junction to maximize electron injection efficiency and suppress hole injection from base into emitter. AuBe/Pd/Au is a typical base contact metallization and AuGe/Ni/Au is often used for the emitter and collector contacts. Finally, a multiple boron damage implant is used for device isolation.

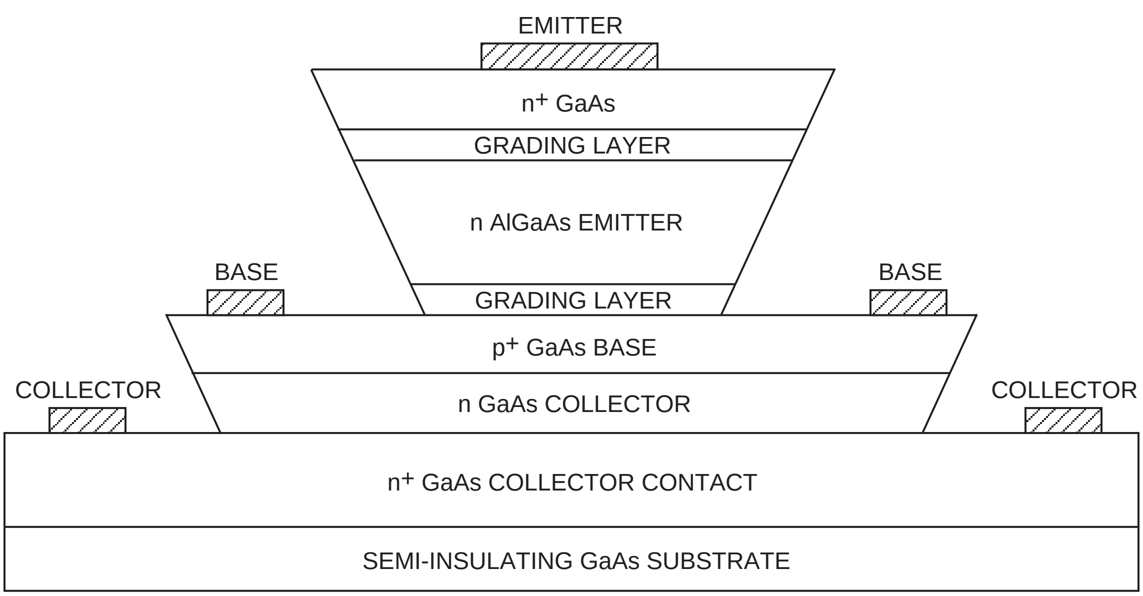

Figure 3-17. Cross section of an example HBT.

A combination of selective (emitter mesa) and nonselective wet etching processes is performed to access the HBT's individual contact. Since base resistance strongly affects HBT microwave performance, it is desirable to place the base contact as close to the emitter as possible. Although advanced lithography is able to define base contacts within 0.1 μm of the emitter, self-aligned (SA) fabrication techniques are more practical because of their low fabrication costs. Although mesa etching is the most common isolation technique for HBTs, ion implantation has been used successfully. A reliability study [1] indicated that isolation by multiple energy implants of fluorine and hydrogen produces stable isolation layers.

Recombination on the exposed extrinsic base surface is a major mechanism of current gain degradation in small geometry AlGaAs/GaAs HBTs. As shown in Figure 3-18, the use of a thin, depleted, AlGaAs ledge surrounding the emitter mesa has demonstrated improved current gain and reliability of HBT devices.

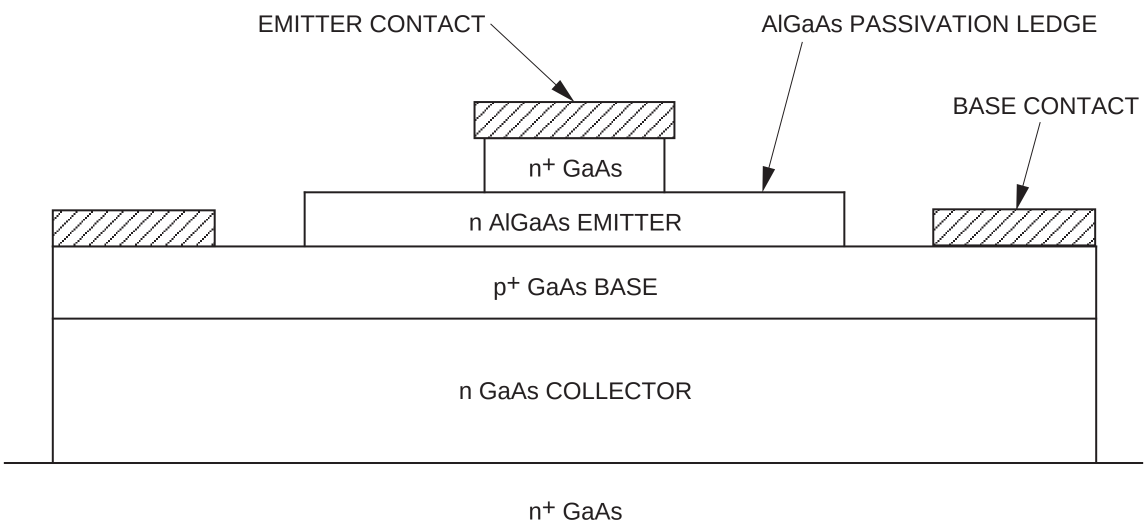

Figure 3-18. An HBT cross section showing a thin ledge of AlGaAs.

Both abrupt and compositionally graded E–B junctions can be used for AlGaAs/GaAs HBTs. Figure 3-19 depicts the energy band diagrams of these two kinds of HBTs. The AlGaAs emitter has a wider band gap than the GaAs base layer. The abrupt E–B junction has a potential spike and notch that can be smoothed out by linear compositional grading on both sides of the AlGaAs emitter over a distance of about 300 Å, thus reducing the barrier that electrons have to overcome.

B. Operating Principles

The potential barriers for hole injection (ΔV_p) and electron injection (ΔV_n) in a graded E–B junction differ by the band-gap difference (ΔE_g) between the AlGaAs emitter and the GaAs base. Therefore, we have

$$q\left(\Delta V_p - \Delta V_n\right) = \Delta E_g \qquad (3\text{-}18)$$

$$\left(\Delta E_g = E_g(AlGaAs) - E_g(GaAs)\right)$$

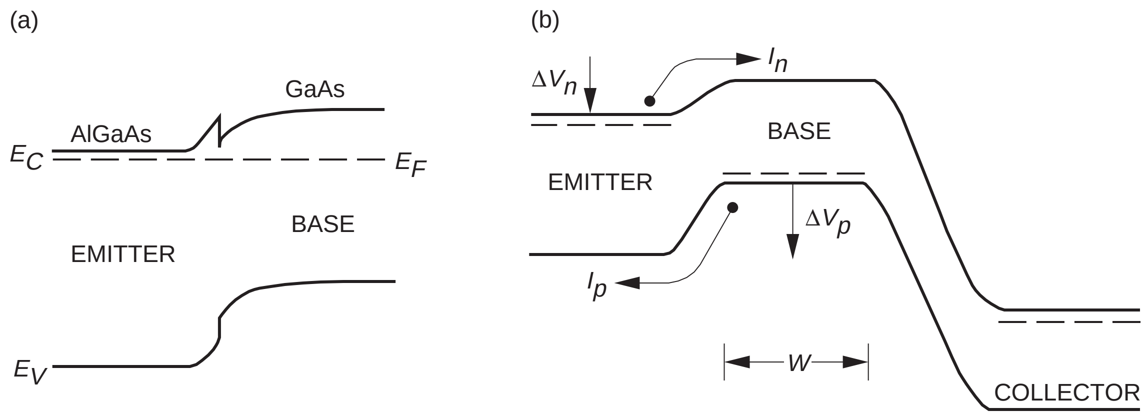

Figure 3-19. AlGaAs/GaAs HBTs: (a) abrupt E–B junction and (b) graded E–B junction.

This small band-gap difference ΔE_g affects the ratio of I_n/I_p significantly where I_n is the electron injection current from the emitter into the base and I_p is the undesired hole injection current from the base into the emitter.

I_n and I_p can be expressed by using the Boltzmann approximation,

$$I_n = qAN_E\left(D_n / W\right)e^{\left(-q\Delta Vn/kT\right)} \tag{3-19}$$

$$I_p = qAN_B\left(D_p / L_p\right)e^{\left(-q\Delta Vp/kT\right)} \tag{3-20}$$

The parameters in Equations (3-19) and (3-20) are q, the electronic charge; k, Boltzmann constant; T, temperature; A, the emitter-base junction area; D_n, the electron diffusivity in the base; W, the base width; N_E, the emitter doping concentration; D_p, the hole diffusivity in the emitter; and L_p, the hole diffusion length in the emitter. Obviously,

$$I_n / I_p = \left(D_n / D_p\right)\left(L_p / W\right)\left(N_E / N_B\right)e^{\Delta Eg/kT} \tag{3-21}$$

For $Al_{.3}Ga_{.7}As$/GaAs HBTs, $\Delta E_g \approx 14.6\ kT$ and exp $(\Delta E_g/kT) \approx 2 \times 10^6$ .Thus, the ΔE_g difference provides a significant improvement in I_n/I_p over the bipolar transistors case ($\Delta E_g = 0$).

This property of HBT devices allows the fabrication of a heavily doped base and a lightly doped emitter without affecting current gain too much. In practice, the base current is dominated by recombination so that common emitter current gain is typically below 100. The low emitter doping concentration decreases the E–B junction capacitance, which affects the current gain cutoff frequency and maximum frequency of oscillation. High doping in the base reduces the base sheet resistivity and base contact resistance, giving rise to the improvement of maximum frequency of oscillation.

C. Reliability

AlGaAs/GaAs HBT technology has reached a certain degree of maturity with insertion into microwave, analog, digital and low-medium-power applications. However, additional reliability data would be needed to warrant widespread acceptance of this class of devices in high-reliability applications requiring high power and high-current-density operation.

HBTs, as other semiconductor devices, have a number of potential failure mechanisms. HBTs typically suffer from current-induced degradation at high-current-density operation. Emitter-base and collector-base leakage currents often originate at the surface of the emitter-base and collector-base junctions, respectively [2]. Thermal and recombination-aided diffusion of crystalline defects from the bulk semiconductor to the heterointerface in abrupt junction HBTs has been suggested to account for increases in base current during burn-in of AlGaAs/GaAs HBTs. Additional evidence of the role of the emitter-base heterojunction was obtained in a study that found that implant-isolated HBTs degrade more than mesa-isolated HBTs [3]. The degradation consisted of a shift in V_{be} and a decrease in h_{FE} , apparently resulting from the contact of the emitter-base junction edge to the defect-laden implant region. Passivation of the emitter junction is important in mesa-isolated HBTs. The use of depleted AlGaAs has given good results.

Beryllium-doped AlGaAs/GaAs HBTs have shown acceptable reliability in accelerated life tests and small-signal applications [4]. However, a more accelerated degradation has been observed on Be-doped HBTs as compared with C-doped HBTs under high-current-density conditions. The suspected cause of device degradation in Be-doped HBTs at high current densities is the field-aided diffusion of positively charged interstitial Be atoms from the base into the AlGaAs emitter, giving rise to V_{be} shift, current-gain decrease, and base and collector current change.

However, as with other semiconductor devices, there are a number of mechanisms by which heterojunction bipolar transistors can fail. The degradation mechanisms that have been reported in heterojunction bipolar transistors include the following:

(1) Decrease in current gain and increase in base-emitter voltage at high emitter currents.

(2) Increases in contact resistance caused by degradation of the interface between the emitter ohmic contact metallization and the emitter semiconductor. An InGaAs contact layer is helpful in solving this problem [4].

(3) Gettering of crystalline defects at the emitter-base heterojunction.

(4) Decrease in current gain and increase in base-emitter voltage for a specified collector current caused by oxidation of the emitter mesa surface in the region of the emitter base heterojunction.

Specialized epitaxy growth for Be-doped-base HBTs, strain-relaxed base layer for C-coped base HBTs [5], the use of an InGaAs emitter cap layer, and emitter ledge passivation are some techniques used to alleviate some observed degradation mechanisms.

HBTs for power applications are designed with a multifinger implementation. In a multifinger layout, the current and temperature distributions on each finger are different, leading to degradation of device power performance. One of the most undesirable phenomena is called “collector-current collapse,” which results in an abrupt decrease of collector current in the devices’ dc I–V characteristics. Figure 3-20 shows typical I–V characteristics in a power HBT with a multifinger design under collector current collapse. The collector-current collapse occurs when a particular finger (usually center) suddenly draws most of the collector current because of its nonuniform current distribution, leading to a decrease of device current gain. Although collector-current collapse has not been observed to cause catastrophic failures on power HBTs, the output power and performance of the device are generally limited. Optimized HBT layout improves power performance and minimizes collector current collapse.

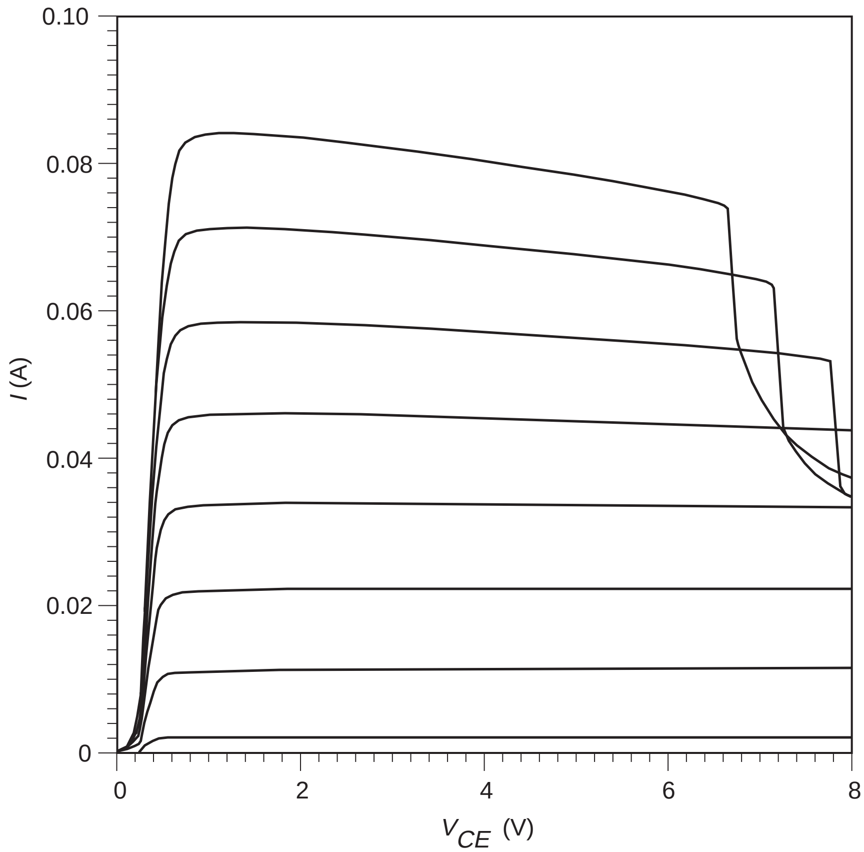

Figure 3-20. Typical I–V characteristic of a power HBT with multifinger design under collector current collapse.

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